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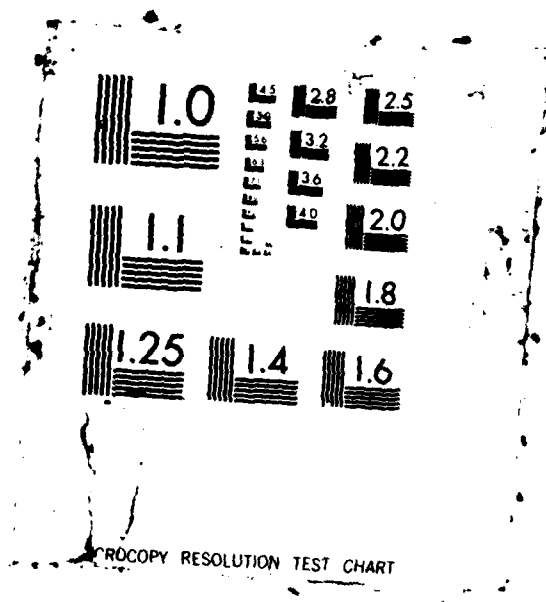
IMPROVED DEPTH AND TEMPERATURE CONVERSION EQUATIONS FOR
SIPPICAN AXBTS (A..(U) NAVAL OCEAN RESEARCH AND
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Executive summary

In October 1985, in a region of large-scale thermohaline staircases off the northeast coast of South America, five shallow and seven deep Sippican AXBTs (air-deployed expendable bathythermographs) were hand-deployed from the USNS *Bartlett* during times when CTD (conductivity, temperature, and depth) casts were being conducted. AXBT temperature and depth values calculated from several standard conversion equations were compared with the CTD values, and improved conversion equations were derived.

Two different elapsed fall-time-to-depth conversion equations were found for the shallow and deep AXBTs, but only one frequency-to-temperature conversion equation. The depth equations, accurate to ± 5 m over the range 0-700 m, were $z = 1.5573t - 0.000301t^2$ for shallow AXBTs and $z = 1.6325t - 0.000215t^2$ for deep, with z the depth in meters and t the elapsed fall time of the probe in seconds. The temperature equation, accurate to $\pm 0.2^\circ\text{C}$ between 6° and 28°C , was $T = -38.6045 + 0.0271075F$, with T the temperature in degrees centigrade and F the transmitted frequency in hertz. *Reynolds Scripps*

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Dr. Henry Perkins, NORDA chief scientist on USNS *Bartlett* cruise 130186, oversaw the gathering of the AXBT and CTD data and made useful comments on the latter analysis. Sippican Ocean Systems, Inc., kindly provided the MK-9 system used to collect the AXBT data, and Robert A. Brown of NORDA installed the system on the *Bartlett* and deduced its operation. Mike Wilcox and Julia Crout of Planning Systems, Inc., did much of the data processing. This work was supported under the Naval Ocean Research and Development Activity Fine Scale Variability Program, U.S. Navy Program Element 61153N, Dr. H. C. Eppert Jr., Program Manager.

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Improved depth and temperature conversion equations for Sippican AXBTs

1.0 Introduction

The air-deployed expendable bathythermograph (AXBT), or AN/SSQ-36, is the standard sonobuoy used by the U.S. Navy to obtain temperature versus depth profiles from fixed-wing aircraft and helicopters. It consists of a standard "A" size sonobuoy container (12 cm in diameter, 91 cm long), a parachute, a VHF transmitter, signal conditioning electronics, a seawater battery, flotation, and a temperature measuring probe. After being launched from an aircraft, a wind flap deployment device separates from the container and pulls out the parachute, which stabilizes and slows the descent of the buoy. Once in the water, the AXBT up-ends, the parachute and canister fall away, the seawater battery activates, and the buoy begins to transmit a carrier signal on one of three standard radio frequencies, 170.5, 172.0, or 173.5 MHz. Thirty to forty seconds later the temperature probe is released.

Changes in water temperature as the probe descends cause a corresponding change in the resistance of the probe's thermistor. The temperature information is converted into an audio range frequency, which is telemetered through a thin wire link to the surface unit where it is used to frequency modulate the transmitted carrier signal. Eventually the thin wire breaks, the transmitter shuts down, and the entire unit is scuttled. Two versions of the AXBT are available, the standard shallow version designed to reach 1000 feet (300 m) and the deep model with a 2500-foot (760 m) depth capability. Characteristics of the AXBT taken from Sippican literature are given in Table 1.

The accuracy of the temperature versus depth profile depends upon the accuracy of the conversion equations, which transform frequency into temperature and elapsed fall time into depth. To check the accuracy of the conversion equations and, if necessary, to develop improved equations, five shallow and seven deep Sippican AXBTs were hand deployed from the USNS *Bartlett* in October of 1985 during times when CTD (conductivity, temperature, and depth) casts were being conducted. The operations region, off the northeast coast of South America, was excellent for such an experiment. The main thermocline between about 150 and 500 m is characterized by large (5–50 m thick), extremely well-mixed layers separated by thin (0.5–5.0 m thick), high-gradient interfaces. An example of these so-called thermohaline staircases, presumably caused by the salt fingering form of double diffusion, is shown in Figure 1.

Table 1. Published characteristics of Sippican AXBTs.

	AN/SSQ-36	AXBT	MIL-8-22354 Performance Req.
Application	Standard probe used by the U.S. Navy for ASW operations	Standard probe used for oceanographic and commercial applications	
Probe Depth	1,000 feet 300 meters	2,500 feet 760 meters	1,000 feet 300 meters
Drop Rate	5.0 ft./sec 1.5 m/sec	5.0 ft./sec 1.5 m/sec	5.0 ft./sec 1.5 m/sec
Time Constant	100 ms	100 ms	100 ms
Spatial Resolution (time constant ÷ fall rate)	0.5 feet 15.24 cm	0.5 feet 15.24 cm	5.0 feet 1.52 meters
Depth Accuracy	± 2%	± 2%	± 5%
Temperature Accuracy	± 0.18°C (to a curve)**	± 0.18°C (to a curve)**	± 0.55°C

* Accuracies of ± 0.1°C are available

** Temperature accuracy curves are derived from the following equations:

1. U.S. Navy specified temperature-to-frequency equation
 $F = 1440 + 35T$, specified accuracy ± 0.55°C
 Where T is °C; F is frequency in Hz
2. Sippican temperature-to-frequency equation
 $T(^{\circ}\text{C}) = -126.852 + 0.216864F - (1.76806 \times 10^{-6}F^2) + (7.70643 \times 10^{-9}F^3) - (1.7688 \times 10^{-11}F^4) + (1.72623 \times 10^{-13}F^5)$
 (Yields temperature accuracy of ± 0.18°C)

2.0 Method and results

All AXBTs for this investigation were manufactured by Sippican Ocean Systems, Inc., of Marion, Massachusetts, to Navy specifications for frequency to temperature and elapsed fall time to depth conversions. Contract and lot numbers and NALC (Naval Ammunition Logistics Code) are given in Table 2.

The Navy-specified depth equation is

$$z = 1.52t \quad (1)$$

where z is depth in meters and t is elapsed time after probe release in seconds. The standard requires the depth to be accurate to ± 5%. Sippican publishes the slightly modified formula

$$z = 1.5926t - 0.00018t^2 \quad (2)$$

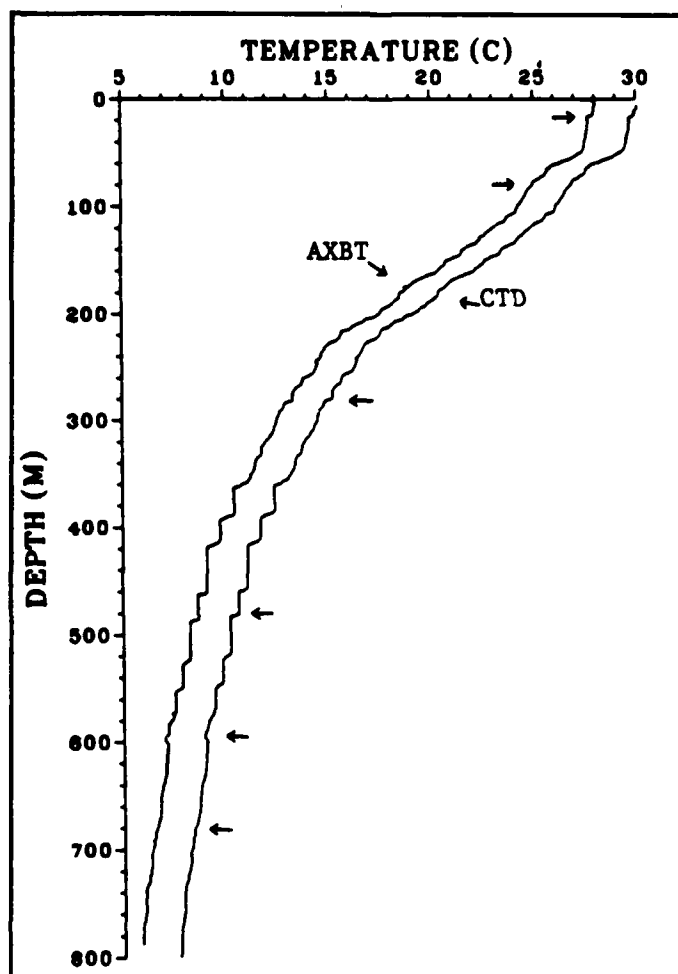


Figure 1. Example of AXBT and CTD profiles. The CTD profile is shifted 2° to the right. The five features selected on this pair for the analysis are indicated by arrows.

Table 2. Contract and lot number and Naval Ammunition Logistics Code (NALC) for the AXBTs used in this study.

Probe Type	Contract Number	Lot Number	NALC
Shallow	N00 163-83-C-0003	13	8W59
Deep	N00 163-83-C-0003	22	8W52

which is supposed to be accurate to $\pm 2\%$ (Bane and Sessions, 1984). The same equations have been assumed to apply to both shallow and deep AXBTs.

The Navy-specified conversion equation for temperature is

$$T = -40.0 \pm 0.02778F, \quad (3)$$

where F is frequency in hertz and T is temperature in °C. The Navy standard requires the temperature accuracy to be

about $\pm 0.55^\circ\text{C}$ within the range from -2° to 35°C , but the probe is known to be considerably more accurate than this amount (e.g., Bane and Sessions, 1984).

Depth and temperature were calculated for the ship-deployed AXBTs by using equations (2) and (3). For each AXBT-CTD pair, five features over the full depth range of the drop were identified on both profiles, and the depth and temperature differences Δz and ΔT calculated. Shallow and deep AXBTs were treated separately, at least initially.

To obtain the depth equation, the differences $\Delta z = z_{CTD} - z_{AXBT}$ were pooled for all shallow and for all deep AXBTs, and linear regressions were done on Δz versus t , the elapsed drop time of the AXBT. The data for the five shallow AXBTs were well fit by either the linear equation

$$\Delta z = -0.05846t,$$

or the quadratic

$$\Delta z = -0.03526t - 0.0001213t^2,$$

with correlation coefficient $r^2 = 0.94$ and 0.95 , respectively. The quadratic was selected, and when combined with the Sippican equation (2), gave the corrected equation

$$z = 1.5573t - 0.000301t^2. \quad (4)$$

The data for the deep AXBTs were well fit by both the linear equation

$$\Delta z = 0.02775t \quad (r^2 = 0.86)$$

and the quadratic

$$\Delta z = 0.03989t - 0.000035t^2. \quad (r^2 = 0.87)$$

Again, the quadratic was selected, and the corrected equation became

$$z = 1.63249t - 0.000215t^2. \quad (5)$$

These results indicate the deep AXBT falls a bit faster than the shallow. This is not surprising, since the deep probe carries more wire and hence weighs more. As will be discussed in Section 3, when applied to the AXBT data, the new equations resulted in the AXBT, and CTD profiles differing by, at most, 5 m and usually less.

A somewhat different technique was used to develop an improved temperature equation. For each data point, frequency was back calculated from T_{AXBT} using the inverse of (3).

$$F = 1440 + 36T.$$

Assuming T_{CTD} to be the "best guess" for the true temperature T , regressions of T (i.e., T_{CTD}) on F were performed. Excellent ($r^2 > 0.99$) linear and quadratic fits were obtained:

$$T = -38.6045 + 0.0271075F \quad (6)$$

and

$$T = -37.5751 + 0.026070F + 0.000024F^2$$

The higher order fit was not significantly better than (6), so the linear relationship was chosen. Initially the data for the shallow and deep AXBTs were analyzed separately. However, no statistical difference was found between the results from the two data sets, so the data were pooled for the final calculations. When applied to the AXBT data, the corrected AXBT and the CTD profiles differed by, at most, $\pm 0.2^\circ$ and usually by much less. A summary of the statistics of these three regression equations is given in Table 3, along with their accuracies described in Section 3.

3.0 Summary and conclusions

The objective of this work was to investigate the accuracy of several of the frequently used AXBT depth and temperature conversion equations and, if necessary, to develop improved equations. Equations (4)–(6) are the outcome. Can they be considered improved, or merely different? The question can be addressed by examining the depth and temperature errors $z_{CTD} - z_{AXBT}$ and $T_{CTD} - T_{AXBT}$ as a function of the best guess for the actual depths and temperatures, z_{CTD} and T_{CTD} .

For the shallow AXBTs, the error in the Navy standard equation (1) appears to be within about ± 2 m up to around 250 m, but subsequently degrades rapidly (Fig. 2). However, it always lies within the required $\pm 5\%$. Equation (2) is actually worse than the Navy standard equation (1) (see Fig. 3), although it, too, is accurate to $\pm 5\%$ up to 300 m. The new conversion equation (4) is a considerable improvement over the previous two formulas (Fig. 4), having errors of about ± 2 m up to about 220 m and ± 4 m thereafter.

The findings are somewhat different for the deep AXBT, but the conclusions are the same. The Navy standard equation (1) consistently underestimates the depth. The error is depth dependent, peaking at about +18 m at a depth of around 400 m and then falling off to around +5 m at a depth of 700 m (Fig. 5). The error, however, still lies within $\pm 5\%$. Equation (2) performs better with the deep AXBT than with the shallow, but underestimates the depth to a maximum of perhaps +15 m near 700 m (Fig. 6). The error is always

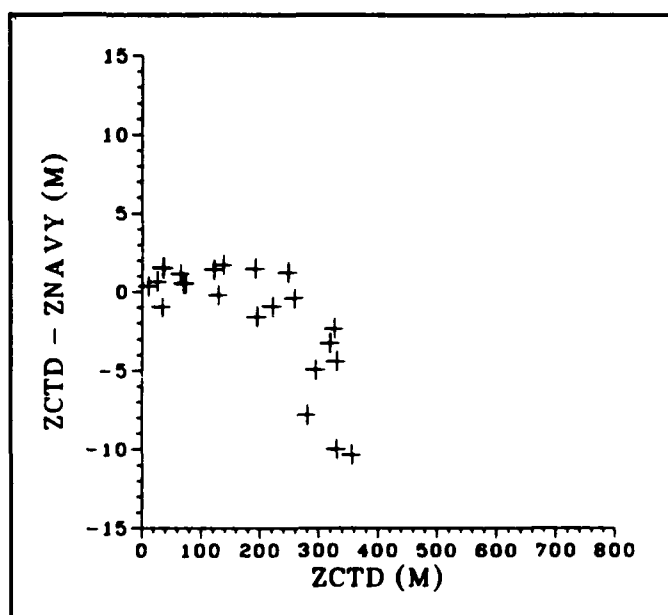


Figure 2. The depth error $z_{CTD} - z_{AXBT}$ for shallow AXBTs using the Navy standard equation $z = 1.52t$.

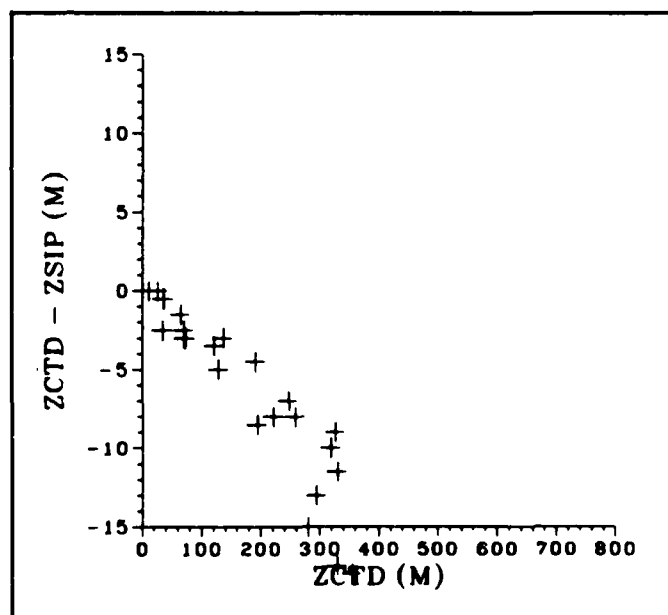


Figure 3. The depth error $z_{CTD} - z_{AXBT}$ for shallow AXBTs using the Sippican equation $z = 1.5926t - (1.8 \times 10^{-4})t^2$.

better than 5% and is generally better than 3%, but does not lie within the claimed 2%. Bane and Sessions (1984) reported the equation

$$z = 1.516t + (1.5553 \times 10^{-5})t^2$$

for initial design-deep AXBTs, a slightly different design from those used here. When applied to this data their equation leads

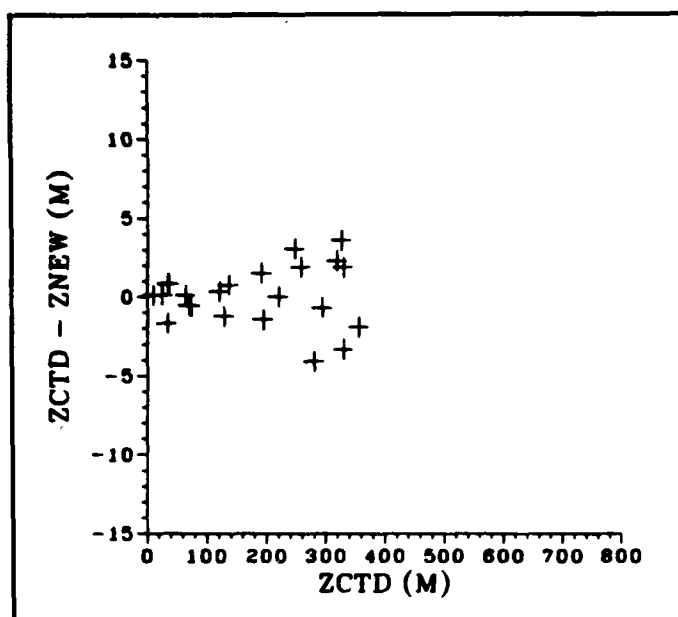


Figure 4. The depth error $z_{CTD} - z_{AXBT}$ for shallow AXBTs using the new equation $z = 1.5573t - (3.01 \times 10^{-4})t^2$.

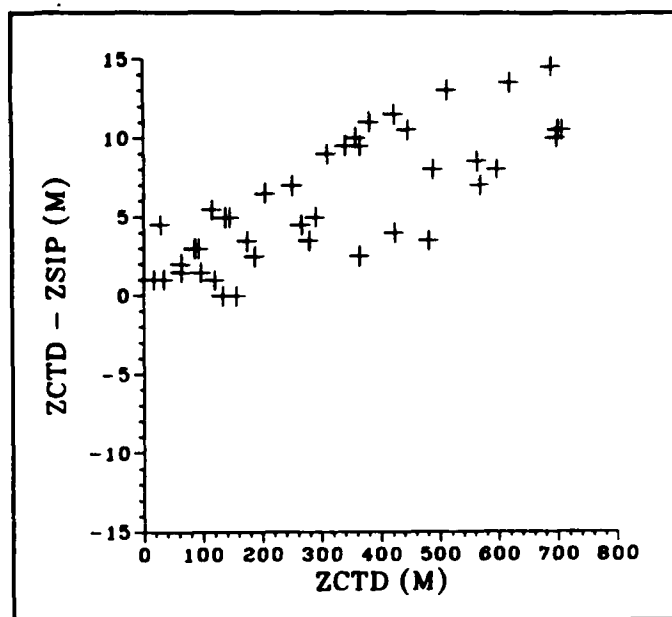


Figure 6. The depth error $z_{CTD} - z_{AXBT}$ for deep AXBTs using the Sippican equation $z = 1.5926t - (1.8 \times 10^{-4})t^2$.

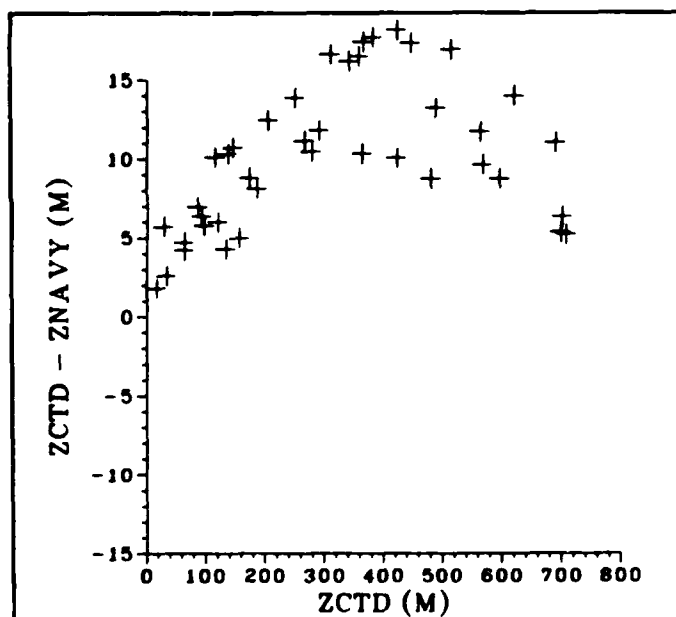


Figure 5. The depth error $z_{CTD} - z_{AXBT}$ for deep AXBTs using the Navy standard equation $z = 1.52t$.

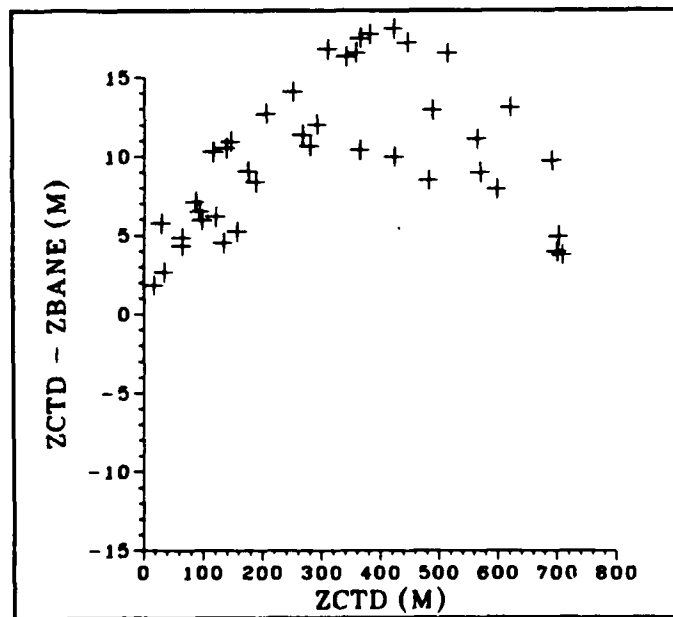


Figure 7. The depth error $z_{CTD} - z_{AXBT}$ for deep AXBTs using the Bane and Sessions (1984) equation $z = 1.516t - (1.5553 \times 10^{-5})t^2$.

to depth-dependent errors quite similar to those of equation (1) (Fig. 7). Their equation does not appear to be any improvement over the Sippican equation (1) for this design deep AXBT. However, the new conversion equation (5) comes out as a considerable improvement over the other formulas (Fig. 8). The depth errors are generally less than ± 5 m and no depth dependency is seen.

The Navy standard temperature conversion equation (3) appears to be accurate to $\pm 0.55^\circ\text{C}$, but the error is a strong

function of temperature (Fig. 9), having its best accuracy in the neighborhood of 15°C . The Sippican fifth-order equation shown in Table 1 overestimates the temperature over the full range investigated, with the actual error being somewhat a function of temperature (Fig. 10). Generally the error is less than -0.5°C , but it does not appear to lie within the claimed $\pm 0.18^\circ\text{C}$. Finally, Gent (1982) reported the results of static temperature calibrations on 48 Sippican AXBTs as giving the temperature conversion equation

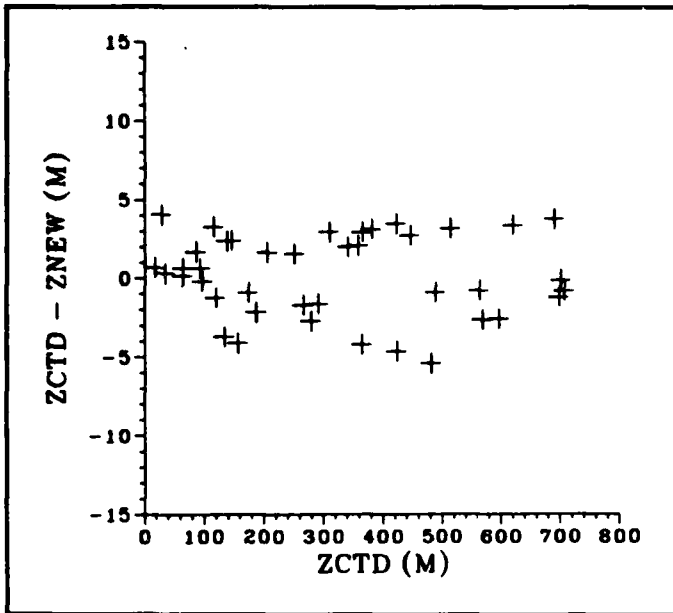


Figure 8. The depth error $z_{CTD} - z_{AXBT}$ for deep AXBTs using the new equation $1.6325t - (2.15 \times 10^{-4})t^2$.

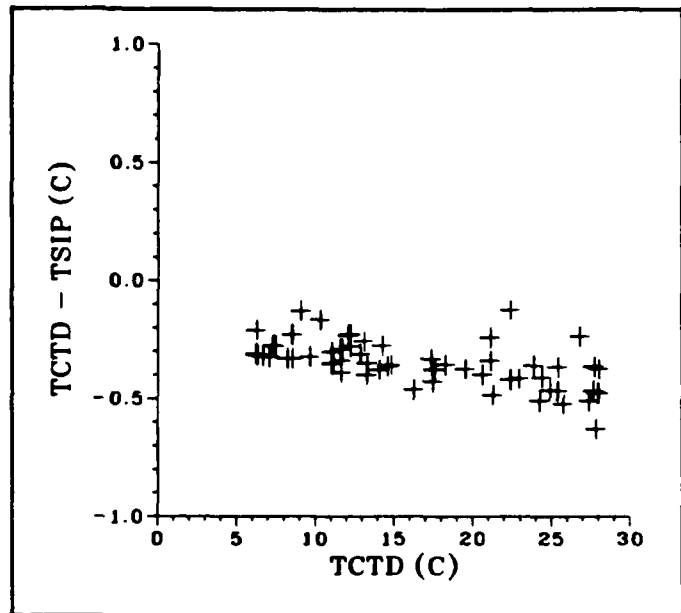


Figure 10. The temperature error $T_{CTD} - T_{AXBT}$ for all AXBTs using the Sippican fifth order equation given in Table 1.

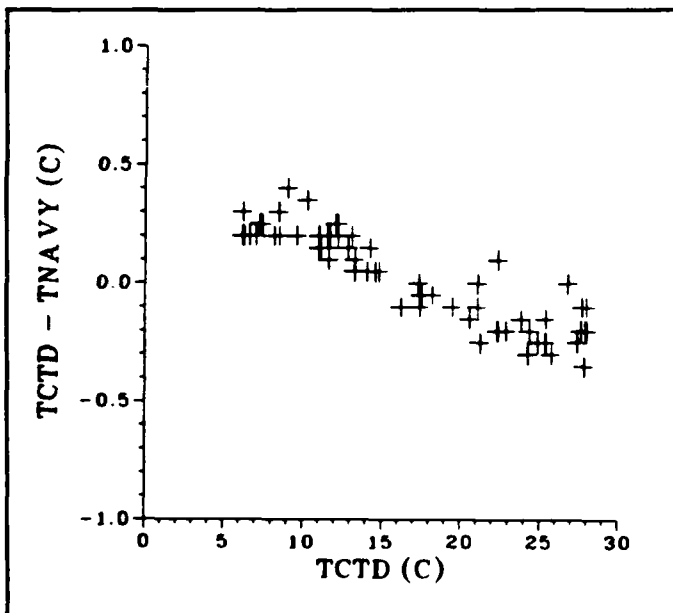


Figure 9. The temperature error $T_{CTD} - T_{AXBT}$ for all AXBTs using the Navy standard equation $T = -40 + (2.778 \times 10^{-2})F$.

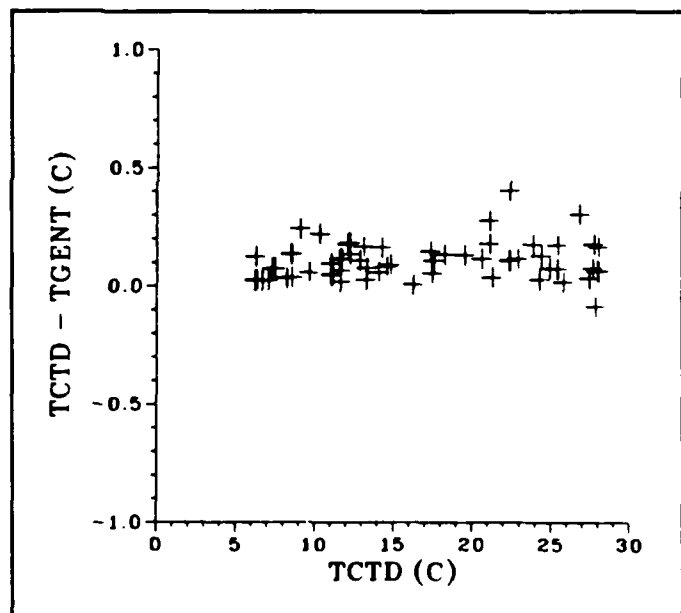


Figure 11. The temperature error $T_{CTD} - T_{AXBT}$ for all AXBTs using the Gent (1982) equation $-66.8857 + (7.0273 \times 10^{-2})F - (2.1807 \times 10^{-5})F^2 + (3.6311 \times 10^{-9})F^3$.

$$T = -66.8857 + (7.0273 \times 10^{-2})F - (2.1807 \times 10^{-5})F^2 + (3.6311 \times 10^{-9})F^3$$

This formula leads to virtually temperature-independent errors for our AXBTs, but appears to underestimate the temperature by about $+0.1^\circ$ (Fig. 11). The new conversion equation (5) is a considerable improvement over at least the first two equations (Fig. 12). By and large, errors lie within $\pm 0.2^\circ$ C and

no particular dependence upon actual temperature is noted, except perhaps for a larger error variability above 20° . The error distribution is similar to that of the Gent equation, but unlike the Gent equation, shows no offset.

In summary, the new depth and temperature conversion equations developed here appear to be real improvements over the older equations considered, at least for the AXBT lot numbers examined. It is unknown if these findings would hold

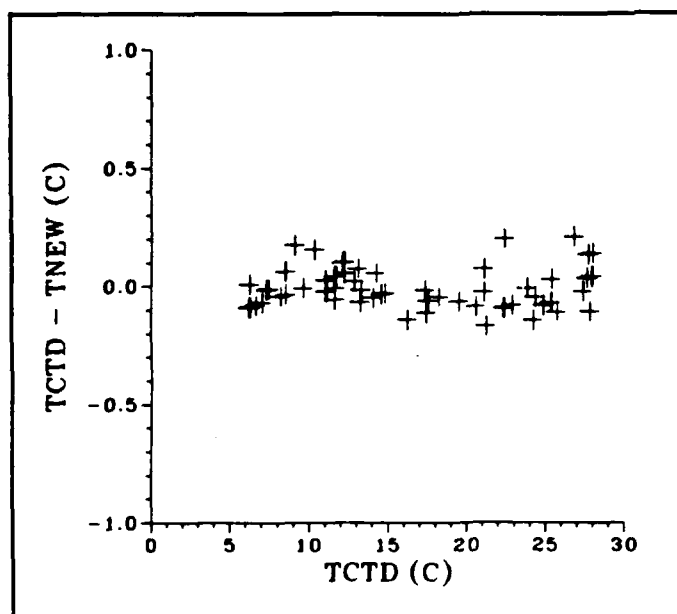


Figure 12. The temperature error $T_{CTD} - T_{AXBT}$ for all AXBTs using the new equation $T = -38.6045 + (2.71075 \times 10^{-2})F$.

for other lot numbers: clearly an examination of this question should be strongly recommended. The temperature offset that appears when using the Gent equation, for example, could be explained by differences in thermistor lots. A summary of the equations in this study and their accuracies is given in Table 3.

4.0 References

- Bane, J. M., Jr., and M. H. Sessions (1984). A Field Performance Test of the Sippican Deep Aircraft Deployed Expendable Bathythermograph. *J. Geophys. Res.*, v. 89, pp. 3615-3621.
- Gent, A. E. (1982). *An evaluation of the airborne expendable bathythermograph (AXBT, SSQ-36 BTS)*. Naval Oceanographic Office, NSTL, Mississippi. Tech. Rep. TR-277.

Table 3. Summary of the depth and temperature equations found in this study.

I. Elapsed fall time t (sec) to depth z (m) conversion equations

$$z = at + bt^2$$

Shallow model:

Coefficient	Value	Standard Deviation
a	1.5573	0.0126
b	-3.01×10^{-4}	0.64×10^{-4}

Accuracy: ± 4 m between 0 and 350 m

Deep Model:

Coefficient	Value	Standard Deviation
a	1.6325	0.0060
b	-2.15×10^{-4}	0.16×10^{-4}

Accuracy: ± 5 m between 0 and 700 m

II. Frequency F (Hz) to temperature T ($^{\circ}\text{C}$) conversion equation

$$T = c + dF$$

Coefficient	Value	Standard Deviation
c	-38.6045	0.0800
d	2.71075×10^{-2}	0.00386×10^{-4}

Accuracy: $\pm 0.2^{\circ}\text{C}$ between 6 and 28°C

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